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# **Development of a Mathematical Model for 'Hayward' Kiwifruit Softening in the Supply Chain**

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Zhao Junyu, Matthew

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## **Abstract**

Fruit loss is a major concern to the kiwifruit industry as it incurs a high cost to monitor and remove over soft or rotten fruit to meet export standards. Kiwifruit is exposed to various temperature scenarios due to different packhouse cooling practices, and temperature control is difficult to maintain throughout the supply chain. Fruit pallet temperatures are wirelessly monitored in the supply chain. This time temperature data provides valuable rich information which could be used to predict kiwifruit quality.

In the laboratory, green ‘Hayward’ kiwifruit were exposed to industry coolchain scenarios to investigate their influence on fruit firmness in subsequent storage. Cooling rate and storage temperature were identified to affect fruit firmness and chilling injury development significantly, where accelerated softening and increased chilling injury development was observed in late storage (> 100 d) when fruit were cooled directly to 0 °C. However, when fast cooled fruit were stored at 2 °C instead of 0 °C, low incidence of chilling injury was observed. The influence of cooling rate and storage temperature on kiwifruit quality suggests that industry should focus on the management practices adopted by packhouses in order to maintain acceptable quality after long term storage. A proportion of the firmness data results were used to develop a mechanistic style mathematical model of kiwifruit softening. Kiwifruit softening was mathematically described based on the correlation with starch degradation, breakdown of cell wall structure, and a description of the incidence of chilling injury development during storage. The model inputs consist of solely commonly collected at-harvest attributes: firmness, dry matter and soluble solids content and time-temperature data. Applying at-harvest attributes as model inputs enabled a capability to predict different softening curves as influenced by fruit maturity, and grower line differences. The developed model

demonstrated promising softening prediction with mean absolute errors (MAE) between 0.8 to 2.1 N when fruit were exposed to fluctuating temperatures and cooling profiles. A logistic model was used to estimate the proportion of chilling injured fruit. Based on the given time temperature information, the logistic model was able to predict the proportion of chilling injured fruit reasonably well ( $R^2 = 0.735$ ). This chilling injury prediction was subsequently used to adjust the softening prediction during the late storage period (>100 d). Model validation was performed using the remaining data, identifying a lack of fit in both the rapid (MAE of 20.8 N) and gradual (MAE of 8.0 N) softening phase. The lack of fit in the rapid softening phase is proposed to be explained by the presence of an initial lag phase in softening which the developed model is unable to predict. The magnitude of firmness associated with starch content and cell wall integrity heavily influenced the lack of fit in the gradual softening phase. Fixing the initial amount of firmness associated to cell wall integrity to be constant for all maturities and grower lines improved the softening prediction.

Overall, this thesis contributes to the challenge of predictively modelling kiwifruit quality in the supply chain. However, there are still many opportunities for improvement including introducing the influence of: variation within the same batch; fruit maturity on chilling injury development; ethylene in the environment; pre-harvest management practices and extending the model to have more focus on high temperature conditions such as those experienced in the marketplace. Conducting studies on: the effect of curing on kiwifruit; using non-destructive techniques to provide information to help define model parameters for prediction; effect of high temperature exposure on kiwifruit softening are possible opportunities that may contribute to enable better prediction of kiwifruit quality in the supply chain in the future.

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## Nomenclature

Symbol	Definition	Units
$a$	Correlationship between starch and firmness	N % <sup>-1</sup>
$AHU_a$	AHU when 50 % of chilling injured fruit is reached	°C d
$AHU$	Accumulated heat unit	°C d
$B$	Soluble solid contents	°Brix
$B_0$	Initial soluble solid content	°Brix
$B_{final}$	Final soluble solids content	°Brix
$F_{CI}$	Lowest firmness measured	N
$CI$	Proportion of chilling injured fruit	%
$CI_{max}$	Maximum proportion of chilling injured fruit	%
$CI_{min}$	Minimum proportion of chilling injured fruit	%
$D_m$	Dry matter content	%
$E_{a,s}$	Activation energy for starch breakdown	J mol <sup>-1</sup>
$E_{a,p}$	Activation energy for breakdown of cell wall structure	J mol <sup>-1</sup>
$F$	Fruit firmness	N
$F_0$	Initial fruit firmness	N
$F_A$	Firmness correlated with starch degradation	N
$F_B$	Firmness contributed by cell wall component	N
$F_{Fix}$	Underlying basal firmness	N
$F_{pred}$	Predicted fruit firmness	N
$F_{soft}$	Predicted soft fruit firmness	N
$k_b$	Rate constant of accumulation of soluble solids content	d <sup>-1</sup>
$k_s$	Rate constant of starch breakdown	d <sup>-1</sup>
$k_{s,ref}$	Rate constant of starch breakdown at T <sub>ref</sub>	d <sup>-1</sup>
$k_w$	Rate constant of the breakdown of cell wall structure	d <sup>-1</sup>
$k_{w,ref}$	Rate constant of the breakdown of cell wall structure at T <sub>ref</sub>	d <sup>-1</sup>
$R$	Universal gas constant, 8.314	J mol <sup>-1</sup> K <sup>-1</sup>
$S$	Starch content	%
$S_0$	Initial starch content	%
$t$	Time	d
$T$	Temperature	°C
$T_{abs}$	Temperature in absolute	K
$T_{ref}$	Reference temperature at 20 °C	K
$T_b$	Base temperature	°C
$\mu$	Rate constant of chilling injury development	d <sup>-1</sup>

Symbol	Definition
Storage conditions	
TB 9	Break in temperature control after 9 weeks of storage
TB 15	Break in temperature control after 15 weeks of storage
HT	High temperature treatments
DH	Different humidity conditions at 30 °C
R <sub>12h,0</sub>	Fruit rapidly cooled to 0 °C within 12 hours
R <sub>12h,2</sub>	Fruit rapidly cooled to 2 °C within 12 hours
D <sub>3d,0</sub>	Fruit directly cooled to 0 °C within 3 days
G <sub>2w,0</sub>	Fruit gradually cooled to 0 °C within 2 weeks
C <sub>1w,0</sub>	Fruit rapidly and gradually cooled to 0 °C within 1 week
C <sub>1w,2</sub>	Fruit rapidly and gradually cooled to 2 °C within 1 week